

Hilltop Supernatural Inflation and Gravitino Problem

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Abstract

In this paper, we explore the parameter space of hilltop supernatural inflation model and show the regime within which there is no gravitino problem even if we consider both thermal and nonthermal production mechanisms. We make plots for the allowed reheating temperature as a function of gravitino mass by constraints from big-bang nucleosynthesis. We also plot the constraint when gravitino is assumed to be stable and plays the role of dark matter.

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1 Introduction

Recent WMAP 7-year data [1] suggest a red spectrum of cosmic microwave background (CMB) with $n_s \simeq 0.96$ which supports the idea of hilltop inflation models [2, 3] where the inflaton sits near the top of a concave downward potential hill when cosmologically interesting scale exit horizon (i.e. the number of e-folds $N = 50 \sim 60$)¹.

The inflation scale is currently an unknown question. We may be able to know it if gravitational waves are detected in the near future, for example, via analysis of B-mode polarization of CMB data from PLANCK satellite [5, 6], the ground-based detectors QUIET+PolarBeaR [7], or KEK's future CMB satellite experiment, LiteBIRD [7, 8]. However, for single-field slow roll inflation we can at least estimate the scale of inflation via dimensional estimation and it seems the most natural value of the scale is grand unification theory (GUT) scale. On the other hand, if we do not restrict ourself by using a single field, (for example, in the case of hybrid inflation, we use two-fields) the scale can be lowered. The reason is one field is used to provide the scalar potential and the other field can have a flatter potential since the end of inflation is determined by the waterfall field to become tachyonic. Although the potential energy is mainly from the waterfall field, the curvature perturbation is from the quantum fluctuation of the inflaton field which is slow-rolling during inflation. The potential form for the inflaton Φ of a hybrid inflation (during inflation) is given by

$$V(\Phi) = V_0 + \frac{1}{2}m^2\Phi^2, \quad (1)$$

where $V \simeq V_0$. The spectrum is

$$P_R = \frac{1}{12\pi^2 M_P^6} \frac{V^3}{V'^2}, \quad (2)$$

where prime denotes derivative with respect to Φ . The spectrum is restricted to be $P_R^{1/2} \sim 5 \times 10^{-5}$ from CMB [1]. We call this CMB normalization in this paper. As can be seen from the spectrum, we can lower the scale of inflation V with a small V' while fixing the spectrum. An interesting possibility is to reduce the scale to a supersymmetry (SUSY) breaking scale. This is the case of supernatural inflation [10, 11] in which a gravity mediated SUSY breaking scale ($V^{1/4} \simeq 10^{11}$ GeV) is chosen. Interestingly, the model can work without fine-tuning with the mass m of order TeV which is the typical soft mass in the framework of SUSY. The characteristic feature of this model is that the spectral index n_s is predicted to be blue ($n_s > 1$), because the potential is concave upward. However, the recent WMAP data suggests it to be red ($n_s \sim 0.96$) [1]. It is well-known that hilltop inflation can produce a red spectrum [2, 3], so it is not surprising that if we can convert supernatural inflation into a hilltop form, the spectral index can be reduced to fit WMAP data². What interesting is that there is a way of achieving this without fine-tuning as well [12]. We call it hilltop supernatural inflation in this paper.

People work on SUSY inflation models know that there is a gravitino problem coming from thermally produced unwanted gravitinos which can put an upper bound for the reheating temperature. It is now becoming well-known also that there may be overproduction of unwanted gravitinos nonthermally by the inflaton decay [13, 14, 15, 16, 17, 18, 19] which may put a lower bound for the reheating temperature. It was shown that many SUSY hybrid inflation models, for example, F- and D-term inflation suffers from this latter type of the gravitino problem.³ It is shown in

¹See Ref. [4] for the general review of inflation models.

²See the type III hilltop inflation model proposed in Ref. [3].

³For example, see also the discussion in Ref. [9] and references therein.

[10] that supernatural inflation does not have former type of the gravitino problem. The hilltop version of it does not change the energy scale nor the waterfall sector therefore the same conclusion applies in both cases. Now a natural question to ask is whether (hilltop) supernatural inflation as a SUSY hybrid inflation has this new gravitino problem. This paper is mainly addressed on this question.

This paper is organized as follows. In Sec. 2, we review the idea of hilltop supernatural inflation. In Sec. 3, we briefly summarize (new) gravitino problem. In Sec. 4, we investigate the allowed reheating temperature as a function of gravitino mass. We consider both constraints from thermally and nonthermally produced gravitinos. We also consider the constraint from gravitino being a dark matter. Sec. 5 is our conclusion.

2 Hilltop Supernatural Inflation

We consider a hybrid inflation from a flat direction in the framework of SUSY which will play the role of an inflaton. A flat direction is normally lifted by supersymmetry breaking terms and non-renormalizable terms with the superpotential

$$W = \lambda_p \frac{\Phi^p}{p M_P^{p-3}} \quad (3)$$

where $p > 3$ and $\lambda_p \sim O(1)$. The scalar potential along the flat direction reads (after minimizing the potential along the angular direction)

$$V(\Phi) = \frac{1}{2} m^2 \Phi^2 - A \frac{\lambda_p \Phi^p}{p M_P^{p-3}} + \lambda_p^2 \frac{\Phi^{2(p-1)}}{M_P^{2(p-3)}}, \quad (4)$$

where the first and second terms on the right-hand side are the soft mass term and the A-term respectively. The last term is simply the F-term potential of the superpotential. For gravity mediation SUSY breaking, we have $m \sim A \sim O(\text{TeV})$. We will focus on the case $p = 4$ (smallest p) and neglect the last term⁴. We hope to add to this potential a (dominated) constant term V_0 during inflation. This can be achieved, for example, by coupling Φ to a waterfall field ϕ via a superpotential of the form [10]

$$W = \frac{\Phi^2 \phi^2}{2M'} \quad (5)$$

where M' is some large mass scale. The potential of the waterfall field (without the above interaction term) has the form

$$V(\phi) = M_S^4 f(\phi/M_P), \quad (6)$$

where M_S is the SUSY breaking scale which we choose as $M_S \simeq 10^{11} \text{GeV} \simeq 10^{-7} M_P$ (gravity mediation⁵). This potential form is common in the framework of SUSY. The explicit form of $V(\phi)$ is not very important. One of the possible choices is [20]

$$V(\phi) = M_S^4 \left(\frac{\phi^2}{M_P^2} - 1 \right)^2 \quad (7)$$

⁴The reason is for our setup the field value of Φ is small enough. Therefore compare with the second term, the last term can be neglected. See [12] for the details.

⁵Our model can work as well for the case of anomaly and mirage mediation because the scale of SUSY breaking and gravitino mass are similar to gravity mediation. For gauge mediation case, one of the authors has considered the consequences in [21].

Another choice may be [10]

$$V(\phi) = M_S^4 \cos^2(\phi/\sqrt{2}M_P). \quad (8)$$

During inflation, when the field value of inflaton is large, a large mass is given to the waterfall field from Eq. (5). This makes $\phi = 0$ and $V_0 = M_S^4$. After inflation, the waterfall field rolls down to its vacuum expectation value (VEV) $\sim M_P$. The value of the mass of ϕ is around $m_\phi \sim O(\text{TeV})^6$.

Hence we obtain a SUSY hybrid inflation which we call *hilltop supernatural inflation*. The potential during inflation is given by [12]

$$\begin{aligned} V(\Phi) &= V_0 + \frac{1}{2}m^2\Phi^2 - \frac{\lambda_4 A \Phi^4}{4M_P} \\ &\equiv V_0 \left(1 + \frac{1}{2}\eta_0 \frac{\Phi^2}{M_P^2} \right) - \lambda \Phi^4 \end{aligned} \quad (9)$$

with

$$\eta_0 \equiv \frac{m^2 M_P^2}{V_0} \quad \text{and} \quad \lambda \equiv \frac{\lambda_4 A}{4M_P}. \quad (10)$$

The number of e-folds is given by

$$N = M_P^{-2} \int_{\Phi_{end}}^{\Phi(N)} \frac{V}{V'} d\Phi. \quad (11)$$

From Eq. (9), we can analytically solve the above integral and obtain

$$\left(\frac{\Phi}{M_P} \right)^2 = \left(\frac{V_0}{M_P^4} \right) \frac{\eta_0 e^{2N\eta_0}}{\eta_0 x + 4\lambda(e^{2N\eta_0} - 1)} \quad (12)$$

$$x \equiv \left(\frac{V_0}{M_P^4} \right) \left(\frac{M_P}{\Phi_{end}} \right)^2, \quad (13)$$

The spectrum and the spectral index are given respectively by

$$P_R = \frac{1}{12\pi^2} e^{-2N\eta_0} \frac{[4\lambda(e^{2N\eta_0} - 1) + \eta_0 x]^3}{\eta_0^3(\eta_0 x - 4\lambda)^2} \quad (14)$$

$$n_s = 1 + 2\eta_0 \left[1 - \frac{12\lambda e^{2N\eta_0}}{\eta_0 x + 4\lambda(e^{2N\eta_0} - 1)} \right]. \quad (15)$$

Since we consider gravity mediation, as mentioned, the natural values of soft SUSY breaking terms, m and A , are $m \sim A \sim O(\text{TeV}) \sim 10^{-15} M_P$. The coupling λ_4 is of $O(1)$, which makes $\lambda \sim O(10^{-15})$. It is interesting that within those natural values, Eq. (14) with CMB normalization can be satisfied and we obtain a successful inflation model with $n_s = 0.96$ which fits WMAP data very well.

⁶This can be estimated for example by $m_\phi^2 \Delta\phi^2 \sim M_S^4$ with $\Delta\phi \sim M_P$. However, we actually require $m_\phi \gtrsim \text{TeV}$ in order for hybrid inflation to end promptly once the mass of waterfall field becomes tachyonic, but too much deviation from TeV would be unnatural. It is also possible to have $m_\phi \lesssim O(\text{TeV})$. In this case, a second stage of inflation could occur. We may consider this in our future work.

3 Gravitino Problem

3.1 Thermal Production

After inflation, both the inflaton and the waterfall field start to oscillate. Before the reheating, actually the oscillating field can be the mixture of the inflaton field and the waterfall field. However, the lifetime of the inflaton field should be shorter than that of the waterfall field because the waterfall field has a large vev of the order of M_P , unlike a negligible value of the inflaton field's vev. This would give a large mass to the inflaton via Eq. (5). Then the energy density of the oscillation should be dominated by the waterfall field. Reheating happens via the decay of waterfall field through gauge or Yukawa couplings [22, 10], therefore the reheating temperature could be higher than m_ϕ . Since we are considering a SUSY hybrid inflation, there could be constraints from gravitino production. In the following, we will first explain the gravitino problem from thermal production. We will consider nonthermal production in the next section and then the constraint to reheating temperature.

To simply illustrate the problem for the thermally-produced gravitino [23, 24, 25, 26, 27, 28, 29, 30, 31, 32], let us start from Boltzmann equation for the gravitino number density $n_{3/2}$

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} \sim \langle\sigma v\rangle n_{\text{STD}}^2, \quad (16)$$

where n_{STD} is the number density of standard particle whose scattering produces gravitino. Then $n_{\text{STD}}/s \sim O(1/g_*) \sim O(10^{-3})$ with $g_* \sim 200$ being an effective number of relativistic degree of freedom in the particle content of the minimal SUSY standard model (MSSM). The gravitino number density $\Delta n_{3/2}$ produced is obtained via solving the Boltzmann equation. We can approximately estimate the solution as

$$\Delta n_{3/2} \sim \frac{\langle\sigma v\rangle n_{\text{STD}}^2}{H}, \quad (17)$$

therefore

$$Y_{3/2} \equiv \frac{n_{3/2}}{s} \sim \frac{\Delta n_{3/2}}{s} \sim \frac{\langle\sigma v\rangle n_{\text{STD}}}{g_* H} \sim \frac{1}{g_*^{3/2}} \frac{T_R}{M_P}, \quad (18)$$

where we have used $\langle\sigma v\rangle \sim 1/M_P^2$ for massive gravitino.⁷ Therefore thermal production of gravitino abundance is *proportional* to T_R . A more accurate solution to the Boltzmann equation for thermal production can be found in [26, 27, 28, 29, 30, 31], which approximately gives

$$Y_{3/2} \simeq 2 \times 10^{-16} \times \left(\frac{T_R}{10^6 \text{ GeV}} \right) \quad (19)$$

Since a large $Y_{3/2}$ conflicts with big-bang nucleosynthesis (BBN), thermally produced gravitino provide an *upper bound* for the allowed reheating temperature [27, 31, 33, 34, 35].

3.2 Nonthermal Production

To illustrate nonthermal production of gravitinos, let us assume our waterfall field ϕ with number density n_ϕ decays into two gravitinos.

$$\phi \rightarrow 2\psi_{3/2}. \quad (20)$$

⁷For simplicity, we are assuming a case of gravitino mass $m_{3/2} \gtrsim m_{\tilde{g}}$ with $m_{\tilde{g}}$ to be gluino mass.

The number density of gravitino $n_{3/2}$ produced is hence given by

$$n_{3/2} = 2n_\phi B_{3/2}, \quad (21)$$

where

$$B_{3/2} \equiv \frac{\Gamma_{\phi \rightarrow 2\psi_{3/2}}}{\Gamma_\phi} \quad (22)$$

is the branching ratio [36, 37, 14, 40]. The waterfall field decays when

$$\Gamma_\phi = H \sim \frac{T_R^2}{M_P} \quad (23)$$

Therefore

$$Y_{3/2} = 2B_{3/2} \frac{n_\phi}{s} \simeq \frac{3}{2} \frac{M_P}{m_\phi} \frac{\Gamma_{\phi \rightarrow 2\psi_{3/2}}}{T_R}, \quad (24)$$

where we have used Eq. (23) and assume the entropy of the universe is from the waterfall field decay. As we can see from Eq. (24), in the case of nonthermal production of gravitino is *inversely proportional* to the reheating temperature. In our model, $m_\phi < \sqrt{m_{3/2} M_P}$, therefore [36, 37]

$$\Gamma_{\phi \rightarrow 2\psi_{3/2}} \simeq \frac{1}{32\pi} \left(\frac{\langle \phi \rangle}{M_P} \right)^2 \frac{m_\phi^3}{M_P^2}. \quad (25)$$

By using Eq. (24), we obtain [39]

$$Y_{3/2} \simeq 10^{-17} \left(\frac{T_R}{10^3 \text{ GeV}} \right)^{-1} \left(\frac{\langle \phi \rangle}{10^{18} \text{ GeV}} \right)^2 \left(\frac{m_\phi}{10 \text{ TeV}} \right)^2 \quad (26)$$

Since a large $Y_{3/2}$ destroys BBN [33, 27, 35], nonthermal production of gravitino provides a *lower bound* for the reheating temperature.

4 Reheating Temperature

Big-bang nucleosynthesis (BBN) put severe constraint on $Y_{3/2}$ (and hence T_R) [33, 27, 34, 35, 31]. The constraint of $Y_{3/2}$ is roughly $Y_{3/2} \lesssim 10^{-17}$. From Eqs. (19) and (26), by using $\langle \phi \rangle \sim M_P$ and $m_\phi \gtrsim O(1) \text{ TeV}$, we plot the constraint of reheating temperature as a function of gravitino mass in Figs. 1, 2 and 3. Here we assumed that the hadronic branching ratio is $B_h \equiv \Gamma_{\psi_{3/2} \rightarrow \text{hadrons}} / \Gamma_{\psi_{3/2}} \sim 1$ ($\sim 100\%$) which is natural in massive unstable gravitino scenario. The dashed line represents the observational bound on the energy density of the cold dark matter (CDM) ($\Omega_{\text{CDM}} h^2 \lesssim 0.1$ reported by WMAP [1]) when a gravitino decays into a Lightest SUSY Particle (LSP) with the LSP mass 100 GeV. Because we did not consider the thermal relic component of the LSP, this gives a conservative bound. When we change the mass of LSP, the constraint can be also changed and scaled accordingly.

We also plot complementary constraints by dotted lines when gravitino is stable and becomes CDM for comparing by using

$$Y_{\text{CDM}} = 4 \times 10^{-12} \left(\frac{m_{\text{CDM}}}{10^2 \text{ GeV}} \right)^{-1} \left(\frac{\Omega_{\text{CDM}} h^2}{0.1} \right). \quad (27)$$

This may be unnatural when gravitino mass is much larger than TeV.

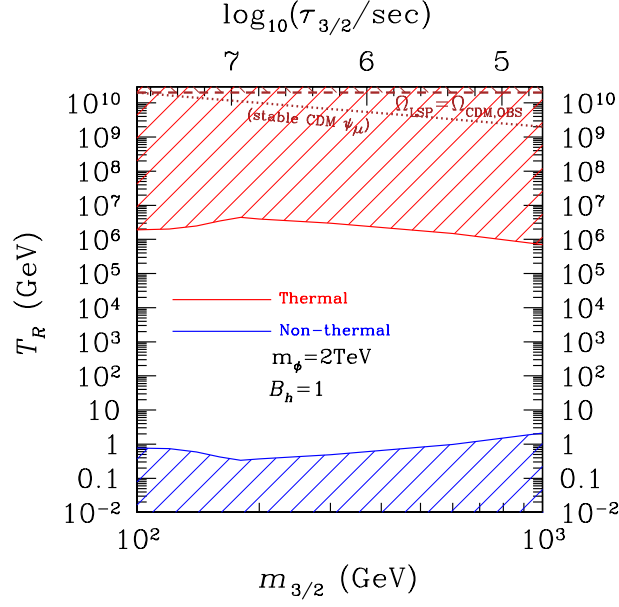


Figure 1: Allowed region in parameter space of T_R versus $m_{3/2}$ with $m_\phi = 2$ TeV. Note that the constraint can be much milder only at around $m_\phi \sim 2m_{3/2}$ because of the suppression of the mode decaying into two gravitinos.

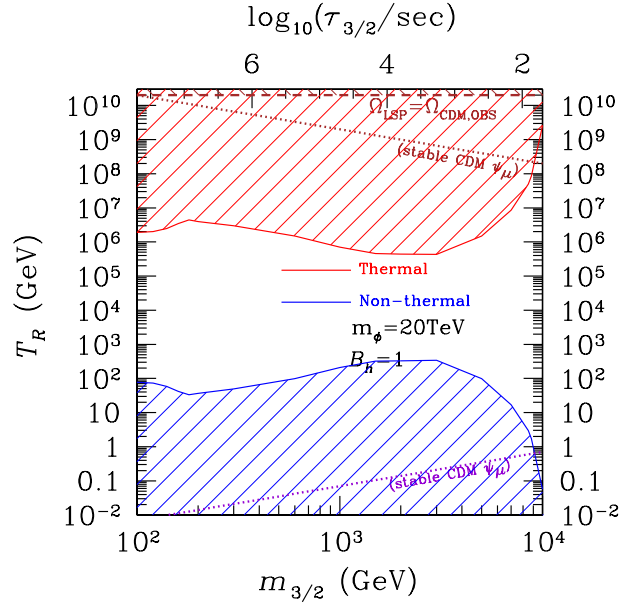


Figure 2: T_R versus $m_{3/2}$ with $m_\phi = 20$ TeV

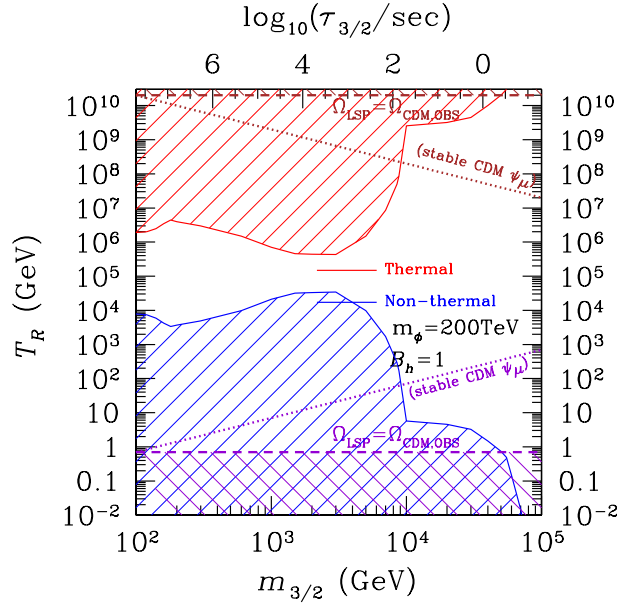


Figure 3: T_R versus $m_{3/2}$ with $m_\phi = 200$ TeV

5 Conclusions

In this paper, we have investigate the allowed regime of reheating temperature as a function of gravitino mass for hilltop supernatural inflation. We consider both constraints from thermally and nonthermally produced gravitino and also in the case when gravitino could become the dark matter. It is not easy to build a SUSY inflation model which requires no fine-tuning of parameters, predict $n_s = 0.96$, and without gravitino problem. Here we have shown that hilltop supernatural inflation can meet all these requirement.

There are some recent works about the effects of waterfall field to primordial curvature perturbation [41, 42, 43, 44]. Those effects are subdominant and our result is not affected although it may be interesting to investigate them as our future work.

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